

The accretion-heated crust of the transiently accreting 11 Hz X-ray pulsar in the globular cluster Terzan 5

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ABSTRACT

We report on a *Chandra* Director's Discretionary Time observation of the globular cluster Terzan 5, carried out ~ 7 weeks after the cessation of the 2010 outburst of the newly discovered transiently accreting 11 Hz X-ray pulsar. We detect a thermal spectrum that can be fitted with a neutron star atmosphere model with a temperature for an observer at infinity of $kT^\infty \sim 100$ eV, and a quiescent thermal bolometric luminosity of $L_q \sim 2 \times 10^{33}$ erg s $^{-1}$ for an assumed distance of 5.5 kpc. The thermal emission is elevated above the quiescent base level measured in 2003 and 2009, i.e., prior to the recent accretion outburst. A likely explanation is that the neutron star crust was significantly heated during the recent accretion episode and needs to cool until it restores thermal equilibrium with the core. Although this has been observed for neutron star low-mass X-ray binaries that undergo accretion episodes of years to decades, it is the first time that evidence for crustal heating is detected for a transient system with a regular outburst duration of weeks. This opens up a new window to study heating and cooling of transiently accreting neutron stars.

Key words: globular clusters: individual (Terzan 5) - X-rays: binaries - stars: neutron - pulsars: individual (CXOGClb J174804.8–244648, IGR J17480–2446)

1 INTRODUCTION

The dense globular cluster Terzan 5 lies in the bulge of the Milky Way Galaxy at an estimated distance of $D = 5.5$ kpc (Ortolani et al. 2007). Terzan 5 contains an exceptionally large population of millisecond radio pulsars (e.g., Ransom et al. 2005), and high-spatial resolution *Chandra* observations have allowed for the identification of many X-ray point sources that are likely quiescent low-mass X-ray binaries (LMXBs) or cataclysmic variables (Heinke et al. 2006).

Neutron stars residing in LMXBs accrete matter from a companion that has a mass $\lesssim 1 M_\odot$. These are often transient systems for which the X-ray luminosity can brighten orders of magnitude due to a sudden strong increase in the mass-accretion rate onto the compact primary. Such accretion outbursts generally reach 2–10 keV X-ray luminosities of $L_X \sim 10^{36-38}$ erg s $^{-1}$, and last for several weeks. Afterwards, the system returns to the quiescent state with a typical X-ray luminosity of $L_q \sim 10^{31-33}$ erg s $^{-1}$, and remains as such for years or decades until it enters a new outburst.

Integral bulge scan monitoring observations signalled X-ray activity in the direction of Terzan 5 on 2010 October

10 (Bordas et al. 2010). The subsequent detection of type-I X-ray bursts (Chenevez et al. 2010) and coherent 11 Hz pulsations (Strohmayer et al. 2010) demonstrated that the active source was a neutron star LMXB, whereas *Chandra* observations provided an accurate localization (Pooley et al. 2010). This new X-ray transient, designated IGR J17480–2446/CXOGClb J174804.8–244648 (J1748 hereafter), is the second confirmed transient neutron star LMXB in this globular cluster (for details on the other one; see Wijnands et al. 2002; Heinke et al. 2003).

Timing of the X-ray pulsations revealed that the neutron star orbits its $\sim 0.4 - 1.5 M_\odot$ donor in ~ 21 h (Papitto et al. 2011). The neutron star is thought to have a relatively strong magnetic field, as inferred from the detection of a broad iron line in the X-ray spectrum ($B \sim 0.7 - 4.0 \times 10^9$ G; Miller et al. 2011), timing of the X-ray pulsations ($B \sim 0.2 - 24 \times 10^9$ G; Papitto et al. 2011) and burst oscillation studies ($B \gtrsim 10^9$ G; Cavecchi et al. 2011).

Figure 1 displays the lightcurve of the 2010 outburst of Terzan 5, as observed with the *MAXI* all-sky X-ray monitor mounted on the International Space Station (Matsuoka et al. 2009). The activity commenced around 2010 October 10 (see also Bordas et al. 2010) and the source soon became very bright, approaching a luminosity of $\sim 10^{38}$ erg s $^{-1}$ (2–50 keV; Altamirano et al. 2010). As can be seen in Figure 1, J1748 remained active until it became

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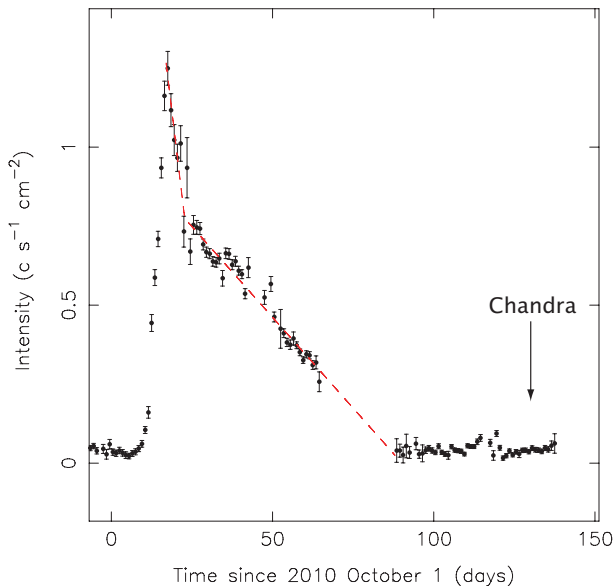


Figure 1. One-day averaged *MAXI* lightcurve of Terzan 5, displaying the 2010 outburst of the recently discovered 11 Hz X-ray pulsar (2–20 keV). The time of our *Chandra* observation is indicated. The dashed line represents a fit with a broken linear decay.

unobservable due to Sun angle constraints in 2010 early-December. Terzan 5 was no longer detected when the *MAXI* monitoring resumed in 2010 late-December, implying a 2–30 keV intensity of $\lesssim 15$ mCrab (Sugizaki et al. 2011) or $L_X \lesssim 10^{35} (D/5.5 \text{ kpc})^2 \text{ erg s}^{-1}$. This indicates that the accretion activity had likely ceased by that time (see Sect. 3.1).

Analysis of archival *Chandra* data revealed that J1748 has a thermal quiescent spectrum (Degenaar & Wijnands 2011). Fits to a neutron star atmosphere model yielded a neutron star effective temperature for an observer at infinity of $kT^\infty = 72.7 \pm 7.6$ eV, and a quiescent thermal bolometric luminosity of $L_q = (6.2 \pm 2.5) \times 10^{32} (D/5.5 \text{ kpc})^2 \text{ erg s}^{-1}$ (Degenaar & Wijnands 2011). Such a soft emission component is often seen for neutron star transients in quiescence and is generally interpreted as thermal emission from the stellar surface. The radiated heat is thought to be generated in nuclear reactions occurring deep inside the neutron star crust during accretion outbursts (e.g., Haensel & Zdunik 2008). These maintain the neutron star core at a steady state temperature, thereby producing a stable level of quiescent thermal emission (Brown et al. 1998).

A small sub-group of transient LMXBs undergo accretion outbursts that persist for > 1 year. Four of such sources were monitored following the cessation of their long X-ray outburst, which revealed that the thermal X-ray emission decayed over the course of years (e.g., Wijnands et al. 2001, 2003; Cackett et al. 2008, 2010; Degenaar et al. 2010; Fridriksson et al. 2011; Diaz Trigo et al. 2011). The observed decrease in thermal radiation has been interpreted as cooling of the neutron star crust, which became severely heated during the prolonged accretion outburst (Rutledge et al. 2002; Wijnands 2004). Confronting the observed cooling curves with neutron star thermal evolution codes gives information about the amount of heat release and thermal conductivity of the neutron star crust, as well

as the properties of the stellar core (Shternin et al. 2007; Brown & Cumming 2009).

The unusually long outburst duration of these quasi-persistent neutron star LMXBs provides the necessary conditions to significantly lift the neutron star crust temperature so that the thermal relaxation becomes observable. However, Brown et al. (1998) argued that in regular transients with outburst durations of weeks, the crust might also become significantly heated above the core temperature, provided that the outburst is bright enough compared to the quiescent base level. As noted by Degenaar & Wijnands (2011), the high outburst luminosity and relatively faint quiescent level of J1748 would then make it a good candidate to search for neutron star crust cooling.

In this letter, we report on a *Chandra* Director’s Discretionary Time (DDT) observation of the globular cluster Terzan 5, obtained after the cessation of the 2010 outburst of the newly discovered 11 Hz X-ray pulsar. The aim of this observation was to study the effect of the bright accretion outburst on the thermal properties of the neutron star crust.

2 OBSERVATIONS, ANALYSIS AND RESULTS

Terzan 5 was observed with the *Chandra*/ACIS-S on 2011 February 17 from 09:06–17:58 UT for 29.7 ks (ID 13225). The cluster is positioned on the S3 chip and the data was obtained in the faint mode with the nominal frame time of 3.2 s. Figure 2 displays an image of the 2011 *Chandra* data, together with a ~ 36.4 ks archival observation that was obtained on 2009 July 15–16 (see Degenaar & Wijnands 2011). It is clear from these images that J1748 is brighter in 2011, ~ 2 months after the cessation of the 2010 activity, than it was in 2009, ~ 14 months prior to that outburst.

For the purpose of directly comparing the new *Chandra* data with archival observations, we use the same analysis and reduction steps as outlined in Degenaar & Wijnands (2011), employing the CIAO software tools (v. 4.2). No background flares occurred during the observation, so all data was used in further analysis. Source count rates and lightcurves were extracted from a $1''$ circular region, centred at the source position, using the tool DMEXTRACT. Corresponding background events were obtained from a circular region with a radius of $40''$, positioned on a source-free part of the CCD that was located $\sim 1.4'$ west of the cluster core.

Our target is detected at a count rate of $(6.5 \pm 0.5) \times 10^{-3} \text{ counts s}^{-1}$, which is about 6 times higher than observed in archival data obtained in 2003 and 2009 (see Degenaar & Wijnands 2011). A total of 192 net source photons were collected. We obtained source and background spectra using the tool PSEXTRACT, and generated redistribution matrices (rmf) and ancillary response files (arf) with the tasks MKACISRMF and MKARF, respectively. We group the spectrum to contain a minimum of 20 photons per bin, and fit the data in the 0.5–8 keV energy range with XSPEC (v. 12.6).

Figure 3 displays the spectrum of J1748, as obtained from our 2011 *Chandra* observation. For comparison, the 2009 spectral data is also shown. Both spectra are soft, with most photons detected below ~ 2 keV. The 2011 spectral data is fitted with an absorbed neutron star atmosphere model NSATMOS (Heinke et al. 2006). We keep the

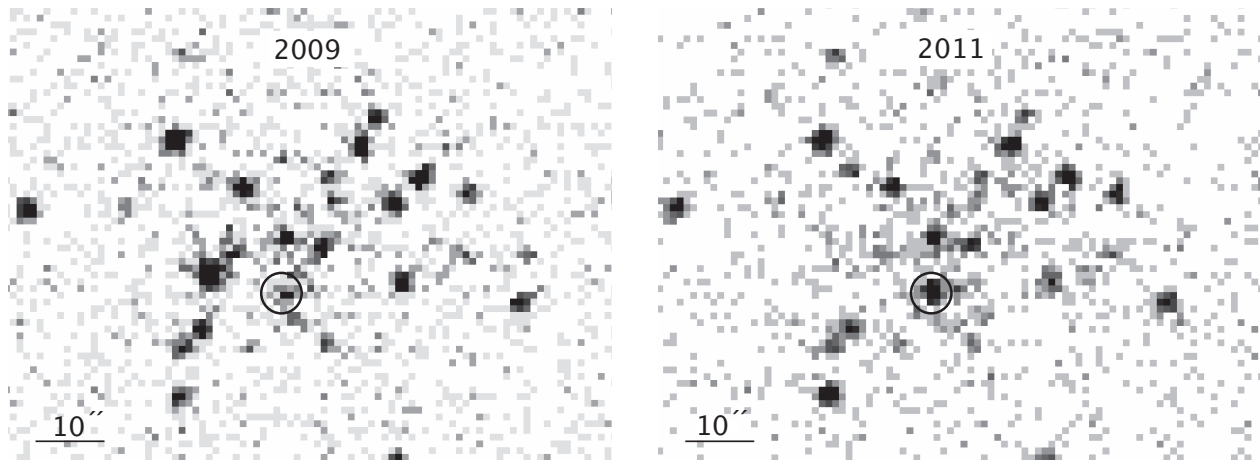


Figure 2. *Chandra*/ACIS images of the Terzan 5 cluster core, indicating the 11 Hz X-ray pulsar that went into outburst in 2010 (circle). Left: Pre-outburst image obtained on 2009 July 15–16, ~ 64 weeks prior to the 2010 accretion activity. Right: Observation performed ~ 7 weeks post-outburst, on 2011 February 17.

distance model parameter at $D = 5.5$ kpc (Ortolani et al. 2007), whereas the neutron star mass and radius are fixed at $M_{\text{NS}} = 1.4 M_{\odot}$ and $R_{\text{NS}} = 10$ km. The model normalization, reflecting the fraction of the surface that is emitting, is set to the recommended value of 1. The only free fit parameters are the hydrogen column density (N_H) and the neutron star effective temperature. All errors reported in this work refer to 90% confidence intervals and the interstellar hydrogen absorption is accounted for by employing the PHABS model.

Fitting the 2011 spectral data yields $N_H = (2.0 \pm 0.4) \times 10^{22} \text{ cm}^{-2}$ and $kT^{\infty} = 98.2 \pm 4.5$ eV, with a reduced chi-square value of $\chi^2_{\nu} = 0.63$ for 6 degrees of freedom (dof). The corresponding 0.5–10 keV unabsorbed flux is $(4.7 \pm 1.0) \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$, and the associated luminosity is $(1.7 \pm 0.4) \times 10^{33} (D/5.5 \text{ kpc})^2 \text{ erg s}^{-1}$. Extrapolation of the model fit to the 0.01–100 keV energy range yields an estimate of the thermal bolometric flux of $(6.9 \pm 1.2) \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$. This implies a thermal bolometric luminosity of $L_q = (2.5 \pm 0.5) \times 10^{33} (D/5.5 \text{ kpc})^2 \text{ erg s}^{-1}$. The NSATMOS model fit is plotted in Figure 3, which demonstrates that the spectral data is described well by thermal emission alone. Adding a powerlaw with index $\Gamma = 1 - 2$, as is often detected for neutron star transients in quiescence, does not improve the fit. This leads us to conclude that any hard spectral component contributes less than $\sim 15\%$ to the total unabsorbed 0.5–10 keV flux.

The hydrogen column density obtained when fitting the 2011 *Chandra* observation is slightly lower than the value retrieved from fits to the 2003 and 2009 spectral data ($N_H = 2.1 \pm 0.9 \times 10^{22} \text{ cm}^{-2}$; Degenaar & Wijnands 2011), although consistent within the uncertainties. To measure the difference in temperature and thermal flux, we re-fitted all data simultaneously, with N_H tied between the different observations. The 2003 and 2009 data were treated as a single spectrum to improve statistics, which is justified because no spectral differences were found between the two observations (Degenaar & Wijnands 2011). For the simultaneous fit we find $N_H = (2.0 \pm 0.3) \times 10^{22} \text{ cm}^{-2}$, while $kT^{\infty} = 72.1 \pm 3.9$ and 100.8 ± 4.3 eV for the 2003/2009 and 2011 data, respectively ($\chi^2_{\nu} = 0.75$ for 16 dof). The corresponding 0.5–

10 keV unabsorbed luminosities are $(3.3 \pm 0.9) \times 10^{32}$ and $(16.0 \pm 3.1) \times 10^{32} (D/5.5 \text{ kpc})^2 \text{ erg s}^{-1}$, while the inferred thermal bolometric luminosities are $(5.9 \pm 1.4) \times 10^{32}$ and $(22.8 \pm 3.9) \times 10^{32} (D/5.5 \text{ kpc})^2 \text{ erg s}^{-1}$.

We note that the employed NSATMOS model does not take into account any effects of the magnetic field on the emerging photospheric radiation (Heinke et al. 2006). This is justified for sources with estimated magnetic fields of $B \lesssim 10^9$ G, but may not be a valid assumption for the 11 Hz pulsar in Terzan 5 (see Section 1). However, magnetized neutron star atmosphere models incorporate field strengths that are well in excess of the estimates for J1748 ($B \gtrsim 10^{12}$ G, e.g., NSA, NSAMAX). Nevertheless, we make a direct comparison between the observations by using the same spectral model, so the fractional change in neutron star temperature and bolometric luminosity as inferred in this work is robust and not caused by any model uncertainties.

3 DISCUSSION

We report on the spectral properties of the newly discovered 11 Hz X-ray pulsar IGR J17480–2446/CXOGC1b J174804.8–244648 in the globular cluster Terzan 5, as observed with *Chandra* within ~ 7 weeks (see below) after the cessation of its 2010 accretion outburst. The quiescent spectrum is dominated by thermal emission that fits to a neutron star atmosphere model with $kT^{\infty} \sim 100$ eV for an inferred thermal bolometric luminosity of $L_q \sim 2 \times 10^{33} (D/5.5 \text{ kpc})^2 \text{ erg s}^{-1}$. Archival *Chandra* observations performed in 2003 and 2009 reveal quiescent spectra that fit to a neutron star atmosphere model with $kT^{\infty} \sim 72$ eV, yielding a thermal bolometric luminosity of $L_q \sim 6 \times 10^{32} (D/5.5 \text{ kpc})^2 \text{ erg s}^{-1}$ (Degenaar & Wijnands 2011).

Our new *Chandra* observation demonstrates that within two months after the cessation of the recent accretion outburst, the thermal flux and neutron star temperature are elevated above the quiescent base level measured in 2003 and 2009. In analogy with that seen for quasi-persistent LMXBs, we attribute this to heating of the neutron star crust due to its bright 2010 accretion outburst. If true, this leads to the

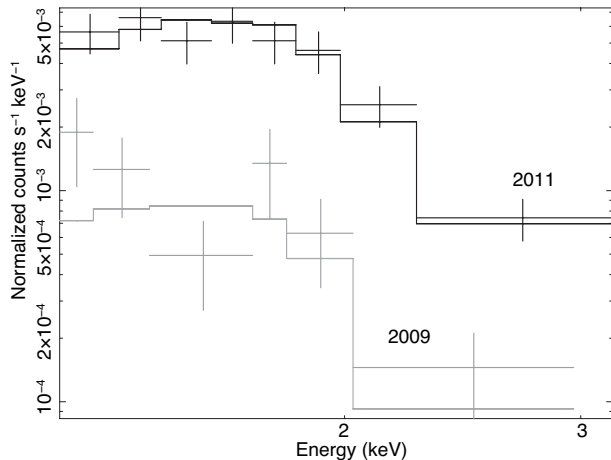


Figure 3. *Chandra*/ACIS spectra of the 11 Hz X-ray pulsar in Terzan 5, as obtained in 2009 (grey) and 2011 (black). The solid lines represent fits to a neutron star atmosphere model.

clear prediction that the crust is expected to cool down in the next months, until thermal equilibrium with the core is re-established and the neutron star returns to its quiescent base level. *Chandra* observations carried out within the next year are thus expected to detect a decrease in neutron star effective temperature and thermal luminosity, down to the values measured in archival data.

An alternative explanation that may be invoked is that the elevated emission level is caused by residual accretion. It has been proposed that low-level accretion onto the neutron star surface produces thermal radiation (Zampieri et al. 1995), and the X-ray spectrum may appear indistinguishable from a passive neutron star atmosphere (Soria et al. 2011). However, there are also indications that low-level accretion involves a hard spectral component. One example is XTE J1701–462, which has been extensively monitored in quiescence with *Chandra*, *XMM-Newton* and *Swift* since its 1.5-yr long outburst ended in 2007 (Fridriksson et al. 2010, 2011). This source exhibits X-ray flares, suggestive of (sporadic) low-level accretion, which are associated with a strong increase in the powerlaw spectral component (Fridriksson et al. 2011). In case of J1748, we detect a purely thermal spectrum, both in the new *Chandra* observation and in archival data. Any possible hard spectral component contributes $\lesssim 15\%$ to the total unabsorbed 0.5–10 keV flux.

Furthermore, the observed quiescent thermal emission may vary a factor of $\sim 2 - 3$ from one quiescent epoch to another, due to the changing amount of fuel and hydrogen/helium abundances present after each outburst. This influences the fraction of heat conducted from the crust towards the core and surface, and hence the observed thermal quiescent emission (Brown et al. 2002). If this is the case for J1748, the quiescent thermal luminosity is expected to remain at the value inferred from our 2011 *Chandra* observation, provided that the accretion has switched off completely.

We consider crustal heating the most likely explanation for the observed elevated quiescent emission of the 11 Hz X-ray pulsar in Terzan 5, but additional *Chandra* observations are required to rule out the above alternative scenarios.

3.1 Outburst constraints

For the purpose of calculating crust cooling curves, it is necessary to constrain the end of the accretion outburst. We therefore try to determine the time at which the source intensity dropped below the detection threshold of *MAXI* (implying a 2–30 keV luminosity of $L_X \sim 10^{35}$ erg s $^{-1}$). Unfortunately, Sun angle constraints deprived our view of Terzan 5 in 2010 December, so that the end of the outburst was not observed (see Fig. 1). The outburst commenced around 2010 October 10 and the source was still active on 2010 December 4. This indicates a minimum outburst duration of 7 weeks (55 days). Since no activity was detected when the *MAXI* monitoring observations resumed on 2010 December 28, the outburst duration is constrained to be < 11 weeks (79 days). Our *Chandra* observation carried out on 2011 February 17, thus took place between 7–10 weeks (51–75 days) after the cessation of the accretion outburst.

We try to refine the estimate of the endpoint of the outburst by fitting the *MAXI* lightcurve to a decay function. After several trials, we found that a broken linear function provides the best description of the decaying part of the lightcurve (see Fig. 1). By extrapolating this fit to later times, we tentatively place the end of the outburst around 2010 December 26 (MJD 55556), although this estimate is subject to the uncertainty in the shape of the outburst decay (e.g., the decay may have accelerated at some point). This suggests that the outburst had a duration of ~ 11 weeks (~ 77 days) and that our *Chandra* observation was thus performed ~ 7 weeks (~ 53 days) after the cessation of the 2010 outburst. The estimated average mass-accretion rate during outburst is $\dot{M} \sim 3 \times 10^{-9} M_\odot \text{ yr}^{-1}$ (Cavecchi et al. 2011; Degenaar & Wijnands 2011).

3.2 Comparison with other sources

We have observed J1748 approximately 7 weeks after the cessation of its 2010 accretion outburst, and found that the thermal bolometric luminosity is elevated by a factor ~ 4 above the quiescent base level, while the inferred neutron star effective temperature is higher by a factor of ~ 1.4 . This is in between the values obtained for the four quasi-persistent neutron star LMXBs that were observed on similar timescales following the cessation of their most recent outbursts: KS 1731–260 (Cackett et al. 2010), MXB 1659–29 (Cackett et al. 2008), XTE J1701–462 (Fridriksson et al. 2011) and EXO 0748–676 (Degenaar et al. 2010; Diaz Trigo et al. 2011). Our results on J1748 thus seems to fit in with the crust cooling detected from the quasi-persistent LMXBs.

Amongst the transient systems with regular outburst durations, Aql X-1 was observed with *Chandra* four times after the end of its 2000 activity. Although the initial two data points suggested a $\sim 50\%$ flux decay, the source intensity had increased in the subsequent observations (Rutledge et al. 2002). Since the quiescent source flux has been found to vary up to a factor of a few (Cackett et al. 2011), there is no strong case to ascribe the observed initial decay in quiescent flux to cooling of the accretion-heated crust. Moreover, Brown et al. (1998) argued that the relatively high quiescent luminosity, compared to the outburst level, would raise the neutron star crust temperature in Aql

X-1 by $\lesssim 1\%$, rendering it unlikely that cooling of the neutron star crust can actually be observed for this particular source.

Another source, XTE J1709–267, was monitored with *Chandra* several times during the decay of its bright 2002 outburst (Jonker et al. 2003). A follow-up pointing obtained ~ 1 year later detected the source at a 0.5–10 keV intensity that was a factor $\sim 2–3$ lower than found ~ 1 month after the outburst (Jonker et al. 2004). These authors noted that the observed flux decay after the outburst was much lower than found for MXB 1659–29, which decreased by a factor of $\sim 7–9$ in a similar time span (Wijnands et al. 2004). However, the observations of XTE J1709–267 are comparable to our results for J1748, so possibly the neutron star crust temperature was elevated after the bright accretion outburst for this source as well.

3.3 Concluding remarks

The results presented in this work suggest that it is possible to detect the effects of crustal heating from transient neutron star LMXBs having regular outburst durations of weeks. This opens up an additional sample of potential targets that can be used for such studies. Promising sources to search for crust cooling once a new accretion episode has passed are those that become bright during outburst, but have a relatively low quiescent luminosity, such as e.g., Cen X-4 (Rutledge et al. 1999; Campana et al. 2004) and 2S 1803–245 (Cornelisse et al. 2007). It will be interesting to probe the differences in crust cooling curves of regular transient LMXBs and their quasi-persistent relatives. Another exciting implication is the possibility to compare the crust cooling curves of a single source after outbursts with different lengths and peak luminosities. In quasi-persistent LMXBs the neutron star crust is expected to be close to a thermal steady-state profile during the long outburst (Brown & Cumming 2009), whereas in transients with regular outburst durations the thermal profile in the crust, and hence the resulting cooling curve, can differ from one outburst to another. This offers new ways to study heating and cooling processes in transiently accreting neutron stars.

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